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L.R. Cornwell

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Texas A & M University
Texas Engineering Experiment Station
College Station, Texas 77843

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THE EFFECT OF AN IMPRESSED ELECTRIC FIELD ON THE METAL WORKING OF AIRCRAFT STRUCTURAL MATERIALS

by

L. R. Cornwell

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TEES
Texas Engineering Experiment Station
Texas A&M University
College Station, Texas 77843

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ABSTRACT

That an interaction exists between conduction electrons in metals and moving dislocations has long been known. Provided a large amount of electrical energy is passed through a metal undergoing plastic deformation either a load drop or increased plasticity is observed. This work confirms that this so called electroplastic effect is strain rate dependent; it becomes negligible at higher strain rates. Thus, it seems unlikely that electroplasticity can be useful in high strain rate metal working operations. However, it might be useful in forming small parts at low strain rates and the required currents do not become excessive. Tensile tests on polycrystalline and single crystal show load drops which become smaller as the strain rate increases. The load drops are considerably higher for single crystals then polycrystals. The possibility of a skin effect due to the very high frequency of current pulses is suggested, and thus the influence of the surface structure in electroplasticity. Other explanations given in the literature are discussed. Mention is made of the effect of small currents on creep and fatigue properties. The necessity for more work on the electroplastic effect is emphasized.

LIST OF FIGURES

I. INTRODUCTION

That there exists an interaction between valence electrons and dislocations in metals has been supposed for some time. This interaction is assumed to take the form of a viscous drag on the dislocations by the valence electrons. Calculations have been attempted to estimate the value of the interaction, for example, Nabarro (1) finds a drag stress of about 1×10^{-3} v Pa, where v is the dislocation velocity. This is a very small interaction and about one-fifth the interaction between dislocations and phonons (1) at room temperature. However, at low temperatures the electron-dislocation interaction may become much larger such that Huffman and Lauat (2) attempted to account for the temperature dependence of the yield stress in bcc metals using this interaction. Measurements of dislocation damping in aluminum by Ferguson, et. al. (3), were explained in terms of an electronic viscosity at low temperatures (below 100°K). Recent studies of plastic deformation in metals in the superconducting state show considerable difference with behavior in the normal state. This work has encompassed internal friction (4), flow stress (5), creep rate (6), and stress relaxation (7). The flow stress of a single crystal of lead, for example, is about 8% higher in the normal state than in the super conducting stage (8). Initial explanations based on a viscous drag mechanism appear to be over-simplified since it predicts a stress difference proportional to the strain rate which is incorrect (9). A recent explanation has been proposed by Granato (10) using an inertial model in which the damping of dislocations in the normal and superconducting states are examined. There does not, however, seem to be general agreement on the nature of the dislocation-electron interaction.

What of the interaction at room temperature, if it is so small how can its effect be demonstrated? Supposing that a large amount of electrical energy is introduced into a metal over a very short time would this produce some change in the plastic deformation behavior? This is exactly what workers in Russia have been doing for the last decade and several studies have been published (11). Current densities of the order of $10^3 A/mm^2$ for 10^{-4}s have been passed through several different crystals such as Zn (12) and load drops found each time the current is passed. The results have been summarized by Okazaki, et al. (11). The Russian work used to describe this effect appears in American translations as "electroplastic effect". Some work of a practical nature has also been done in the area of rolling and wire drawing. Klimov, et al. (13), claim to have cold rolled highly cold worked wires of tungsten and W-Re alloys to microribbon 20-30 μm thick. Very few details are given, but it appears that a continuous high density current was passed between the rolls via the sample. Heat was removed by spindle oil such that the temperature rise was <200°K. Spitsyn, et al. (14), have drawn wires of stainless steel (18 Cr 9 Ni .5 Ti) through dies ranging from 0.93 to 2.2 mm at speeds between 20 and 35 m/min. The current conditions were, frequency 90-200 Hz, density 400-500 A/mm^2 and pulse duration 30 x 10^{-6} sec. Heating of 15 to 220°K was observed and a reduction in tensile strength of up to 17% determined. The maximum reduction in strength was for the smallest diameter wires, but it is not clear whether this was simple a result of a larger current density or not. Other investigations have appeared in the Russian literature in which auxillary effects have been studied. For example, the pinch effect due to a current pulse (15), resistivity changes (16), influence of a pulsed magnetic field on creep rate (17), irradiation by electrons (18-20). A review by Troitskii on "Radiation and the Plasticity of a Metal" has been published (19).

Another set of experiments worth noting are those in which creep rates are changes by electric fields. In this case, however, steady DC current is passed at much lower current densities. Only when the current is switched on or off is a change in creep rate observed (21,22). The creep rate can either increase or decrease depending on the metal and the way the electric field is applied. It was further shown (22) that simply by connecting a metal under creep conditions to another metal, a change in the creep rate could be observed. Evidence was presented (22) of a structural change in the surface layers of Ni caused by the application of an electric field. Microhardness measurements and X-ray diffraction showing line shifts, were used for this purpose. These results were interpreted in terms of a charged surface layer and its interaction with structural defects. A study of the influence of an electric current on the low-cycle fatigue of steel using a low current has also been published (23). It was claimed that the endurance in all media used air, 3% NaCl solution and hydrogen, was improved. Based on metallographic evidence, the improvement was explained in terms of a more uniform dislocation distribution both at the surface and in the interior.

The work reported here attempted to determine the magnitude of the electroplastic effect in cold rolling aluminum and in tensile testing both single and polycrystals of aluminum.

II. EXPERIMENTAL PROCEDURE

Initial work showed only a small drop in rolling load when an electric current was passed through aluminum during cold rolling. It was therefore decided to pass current through tensile specimens where the strain rate is much lower. The specimens were 99.999% polycrystalline aluminum form Materials Research Corporation, .150 diameter, 2 in. gauge length. They were annealed and electropolished with a grain size of 100 μm. Single crystal specimens of random orientation were also used; they were 99.996% aluminum from M-Structures, Inc. The gauge length was 3 in. and rectangular cross-section of .25 in. by .125 in. Both sets of specimens were clamped in holders which were electrically insulated from the frame of the Instron tensile testing machine. Current was supplied by heavy copper loads directly to the holders from a DC constant current power source. This power supply incorporated a bank of capacitors so that when it was switched on a very high current was discharged through the specimen. The current could then be either switched off or, if left on for a few seconds, would reach a stable DC current dictated by the power setting, e.g., 200 amps. The high current pulse produced a current density of 370 amps/mm^2 for 10^{-4} secs on the polycrystalline specimens and 250 amps/mm^2 on the single crystals. In some tests, the current was left on for 3 seconds after which specimen heating became excessive. For short times, the temperature rise was below 13°C as measured by an iron-iron constantan thermocouple attached to the specimen.

The current was pulsed through the specimen during the plastic region of the load elongation curve initially at a strain rate of 1×10^{-3}/sec. On some polycrystalline specimens, the strain rate was varied up to a maximum of 0.1/sec. The single crystal specimens were tested at one strain rate. Two polycrystalline specimens were sectioned for transmission electron microscopy after equivalent strains, one with current passage and one without.

III. RESULTS

1. Polycrystalline Aluminum

The effect of passing a current through an aluminum polycrystalline tensile specimen is shown in Fig. 1. Load drops are observed when the current is switched on for a fraction of a second. The rise in load when the current is switched off is more gradual than the load drop. Increasing the voltage which increases the current causes larger load drops is also shown in Fig. 1. Plotting the magnitude of the load drops as a function of voltage produces a graph shown in Fig. 2. Clearly, the higher voltages produce increasingly higher load drops.

When the strain rate is increased, the magnitude of the load drop decreases and virtually disappears at the highest strain rates. For these experiments, the current was left on for 3 seconds to produce curves schematically illustrated in Fig. 3. The initial peak current was 370 amps/mm^2 which reduced to 20 amps/mm^2 during a plateau which appeared in the curve. As the strain rate increased, the plateau length decreased and eventually disappeared. The load drop becomes smaller on further increase of the strain rate. Whem compared to the stress-strain curve for a specimen tensile tested without current, the curve from a specimen with current was lower. Only two specimens, one with and one without current, were examined by TEM. The microstructures examined did appear to show a difference at a strain level of 15%. The specimen with current showed regions where a cell structure was being developed which were absent in the other specimen.

2. Single Crystals

Application of a current during tensile straining of randomly oriented single crystals produces large load drops as illustrated by the load elongation curve in Fig. 4. The effect of voltage and, hence, current is shown in Fig. 5 for different values of strain rate. The highest load drop measured was 50% of the applied load. The influence of strain rate is very marked as shown in Fig. 6 where a rapid increase in load drop occurs for the lowest strain rates. Attempts to determine the effect of crystal orientation on the magnitude of the load drop were not successful due to the large diameter of the available crystals (.25 in.). This simply made the current density too low to produce any kind of significant load drop.

IV. DISCUSSION

This work confirms results in the literature that a high density current passing through a metal undergoing deformation will momentarily change the metal's response to the deformation conditions. Also confirmed is that increasing the current density and decreasing the strain rate both increase the change in the metal's response to deformation. No mathematical relationship has been suggested which related the cause and effect. The electroplastic effect seems applicable to all metals, but the magnitude of the response does not appear to be related to the electrical conductivity. For example (11), iron shows a much larger load drop than tin, but the conductivities are roughly the same.

Most Russian authors rely on a calculation by Kravchenko (24) for an explanation of electroplasticity. He argues that there is an energy transfer by Cerenkov radiation between electrons and dislocations. If there is a current flowing and the electrons are moving faster than the dislocations, then energy is transferred to the dislocations which ultimately makes plastic flow easier. Conversely, if the drift velocity of the electrons is less than that of the dislocations, the reverse occurs. Several authors (11,12,13,25) have included calculations of electron drift velocities and estimates of dislocation velocities which usually show the former to be greater. The results, however, are not always unambiguous and given the limited accuracy of dislocation velocity estimates the above explanation is not well established.

An inherent problem with the simple idea of electrons accelerating dislocations is the effect on dislocations travelling in the reverse direction. One would expect these electrons to be slowed down and, thus, reduce the overall effect of current flow on plasticity. Perhaps to counter this objection, another approach is to argue that the electrons help dislocation pile-ups to overcome obstacles or assist dislocation sources (15,25). A variation of these ideas is to think of the electrons as causing changes in the dynamics of vibrating dislocation segments which leads to a decrease in the time to overcome obstacles (15,25). This is really an inertial model and appears to be similar to a recent approach to account for enhanced plasticity in the superconducting temperature region (10). There is, however, a distinct difference in deformation in the superconducting region and electroplasticity. The enhancement of plasticity in the superconductivity condition as compared to the normal condition is independent of strain rate whereas in electroplasticity it is strain rate dependent.

Whatever mechanism is used to explain electroplasticity must account for the reduced load drops as the strain rate is increased. If we take strain rate $\dot{\epsilon} = \rho b\bar{v}$, where ρ is the mobile dislocation density, b the Burgers vector and $\bar{v}$ the dislocation velocity then since $\bar{v}$ is stress dependent, a decrease in $\bar{v}$ will cause a drop in stress. This could be caused by an increase in ρ which would result in $\bar{v}$ decreasing at a constant strain rate. However, the stress dependence of dislocation velocity is very low in fcc metals so it is difficult to see a significant load drop on this basis. Furthermore, an increase in dislocation density caused by a current flow should be independent of strain rate then this would result in a load drop which experimentally is not the case. Thus, an explanation in terms of the current assisting dislocation over barriers or alternatively lowering barrier would seem more appropriate.

There has been little discussion in the literature of the influence of current direction and its relationship to the direction of dislocation motion. The fact that polycrystalline specimens undergo load drops disprove the idea that electrons would enhance dislocation motion in one direction and hinder motion in the opposite direction with zero net effect. Yet it appears from the results presented here for single crystals do suggest some role for orientation effects. This result was also found by Troitskiy and Ronzo (12) for differently oriented single crystals of Zn. Further evidence for an orientation effect is supplied by Troitskiy (27) who irradiated a single crystal of zinc while undergoing tensile straining and current pulses with an electron beam. The direction of the beam coincided with primary slip direction can be visualized as being aided by the electron flow. Since the load drops in polycrystals are much less than in single crystals, the number of dislocations being aided would appear to be considerably less.

One aspect of the current pulses which has received little attention is the fact that the short time involved simulates half a cycle of an AC current. The frequency is high enough to consider the possibility that current flows in the surface only, i.e., the well known skin effect for RF alternating current. If this is so, then the mechanical behavior of the surface layer obviously becomes important. Klypin (22) discussed the importance of the surface layer although under different experimental conditions. He considered the influence of a charged surface layer in creep experiments under a continuous DC current of low voltages. He suggested, following Kramer (28), that piled-up dislocations in subsurface layers act as barriers to plastic flow. Presumably then, if a skin effect were present, electron flow would assist dislocations through these barriers. Hence, the skin effect would be more important in very small diameter specimens where the surface layer takes up a considerably volume of the cross-section. This is exactly what Okazaki, et al. (11) found in their study of electroplasticity in titanium. For the same current density, the load drops increased rapidly as the diameter became small (~0.1 mm). Thus, those properties which are influenced strongly by the surface conceivably could be altered by HF current pulses.

While this approach does not appear to have been used, others have investigated the effect of a steady DC current under the premise that surface properties will be affected. As previously noted, Klypin (22) studied creep rates of various metals under currents from 1-100 volts and found changes in creep rates when the current was first applied and when it was removed. He emphasized the presence of a charged surface layer which is changed by the application of a current, hence, affecting the deformation properties. No details of the mechanism were suggested.

An important property influenced by the surface is that of fatigue. Karpenko, et al., (23) studied the low cycle fatigue of steel in different environments with and without a low density DC current. Their results show that the fatigue endurance of the steel was enhanced by the DC current. Metallographic investigations showed that the dislocation structure was more uniform in samples with current and that structural changes occurred later than in those without current. Very little explanation was given for the observations except to suggest that electron flow impedes the build up of dislocation structures normally found in fatigue microstructures. Thus, a uniform microstructure supposedly increases the endurance and the resistance to a corrosive environment. Since the current density in the experiments was only 0.07 A/mm^2, it seems hard to imagine the mechanism which affects properties being the same as that for pulsed high cement density DC current. A further suggestion (29) raises the possibility that a surface oxide such as found on aluminum, might play a role in determining the way a current affects the properties.

Two Russian papers (22,23) describe changes in microstructure due to the passage of current. On the other hand, Okazaki, et al. (11) in their work on titanium, found that the envelope of the stress-strain curve was identical for specimens tensile tested with and without current. They thus concluded that electroplasticity did not change the microstructure. The Russian experiments were different in that constant DC low density currents were used in contrast to pulsed high current densities used by Okazaki, et al. In the work reported here, microstructural differences were noted in two polycrystalline Al specimens strained 15%. The specimen deformed under pulsed current showed a more developed cell structure than one deformed without current, when examined by TEM. Furthermore, the envelope of the stress-strain curve for the former was lower than that for the latter. However, based on the limited sampling this can only be described as a tentative result and can only be decided by sectioning single crystals of known orientation. These conflicting results may also reflect differing behavior between various metals studied.

One effect that occurs when a current is passed through a metal and has not been mentioned before is electromigration. Under the influence of an electric field, atoms can migrate down the gradient. In principal, this is mass flow and could change the length of a specimen resulting in strain. However, the atomic drift velocities are very low (30) and, furthermore, should be independent of strain rate. Thus, electromigration is not thought to be important during electroplasticity.

V. SUMMARY

The work of other investigators and the results reported here indicate the following:

1. That when a high density current is passed through a metal undergoing plastic deformation there is either a sudden load drop or an increase in plastic strain.

2. The magnitude of the load drop increases as the current density is increased.
3. For a fixed current density the magnitude of the load drop decreases as the strain rate increases.
4. For the same conditions, single crystals show larger load drops than polycrystals.
5. The alignment of the direction of the current with the direction of direction of dislocation motion appears to enhance the magnitude of the load drops.
6. There does not appear to be any relationship between electrical conductivity and the magnitude of the electroplasticity effect.
7. For the same conditions, lowering the temperature appears to increase the electroplastic response.
8. No satisfactory explanation for electroplasticity has been given as yet.

VI. CONCLUSIONS

Electroplasticity is a real effect in metals which is not well understood. Its potential for use in the fabrication of metals needs much more exploration but must be restricted to low strain rate metalworking operations. The effect of electroplasticity in phenomenon such as creep and fatigue whether by high or low current densities needs detailed investigation.

The electroplastic effect in metals appears to be fertile field for further research effort and the extension to non-metallic materials worth considering.

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VIII. APPENDIX I

Publications

S. K. Varma and L. R. Cornwell, "Electroplasticity in Al," presented at the Annual Meeting, AIME, New Orleans, February 1979.

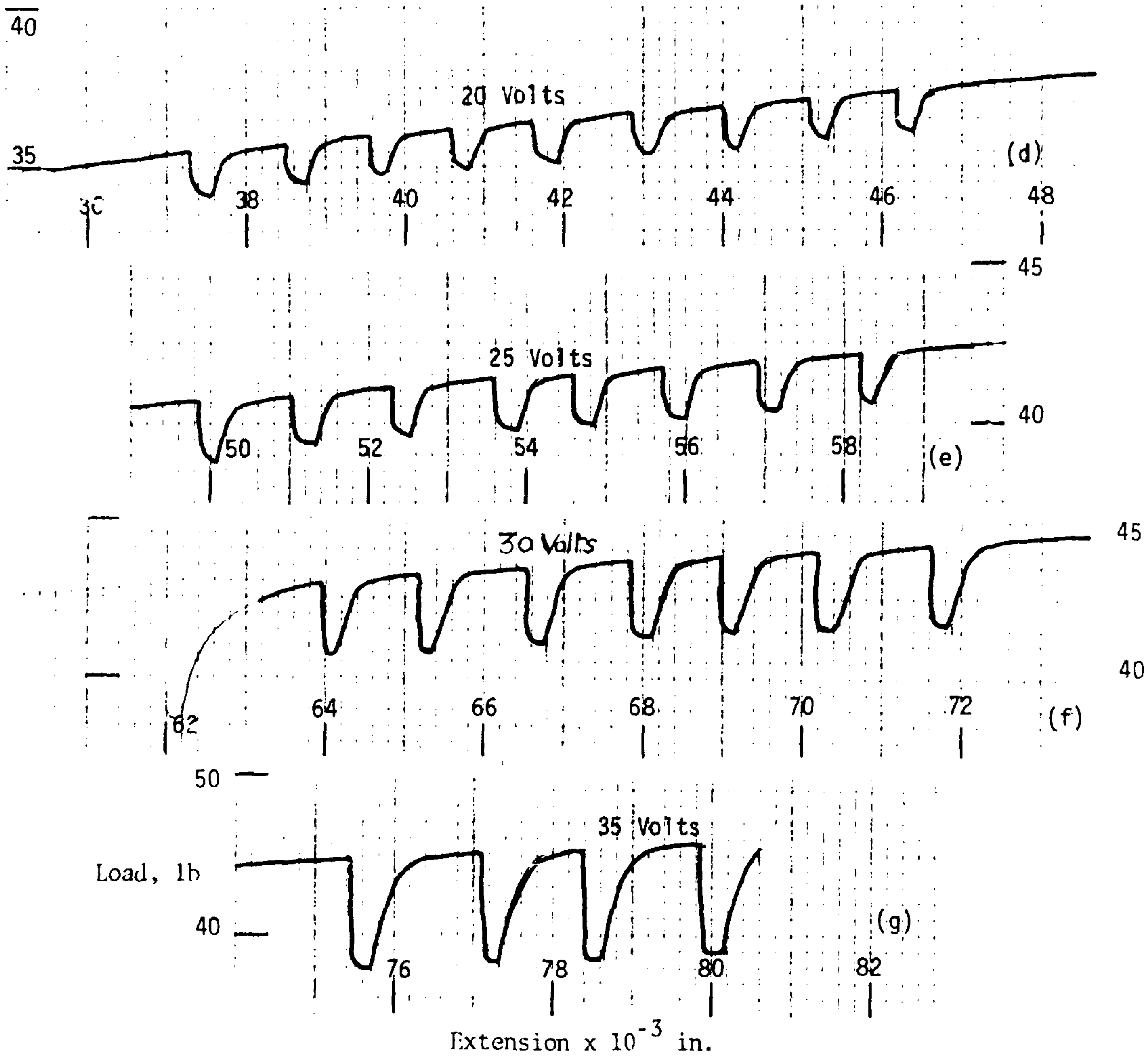


Figure 1: Effect of voltage on magnitude of load drop for polycrystalline Al

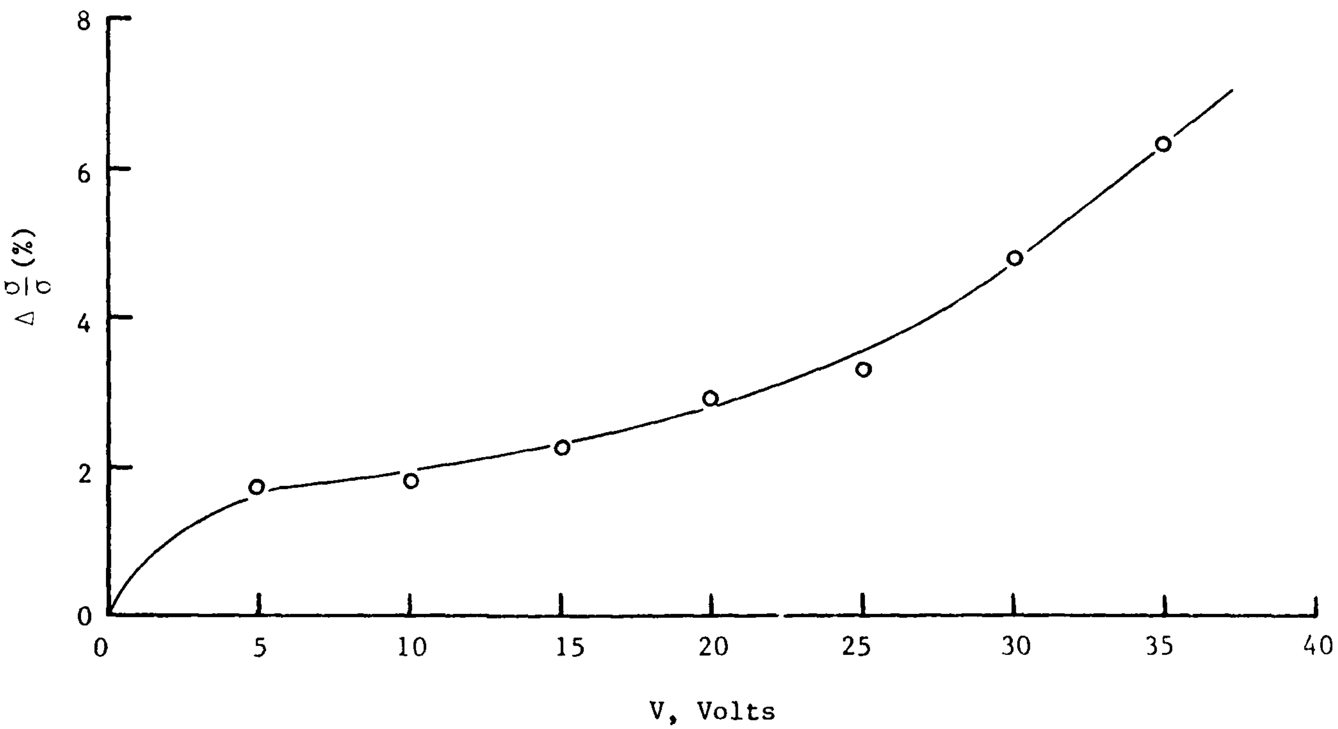


Figure 2: Variation of Load Drops $\Delta\ \sigma/\sigma$ (%) With the Voltage in Polycrystalline Aluminum in Tension.

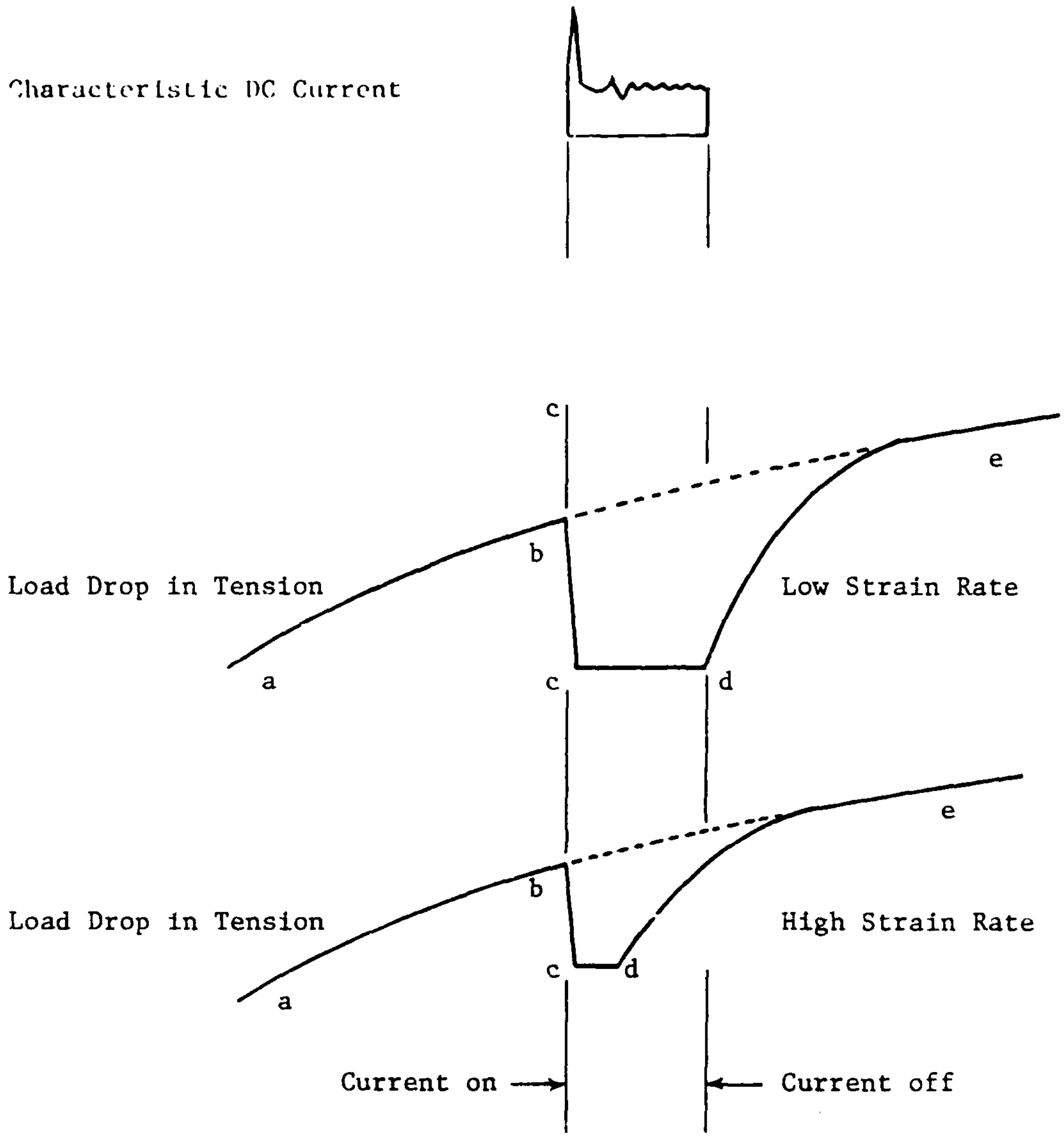
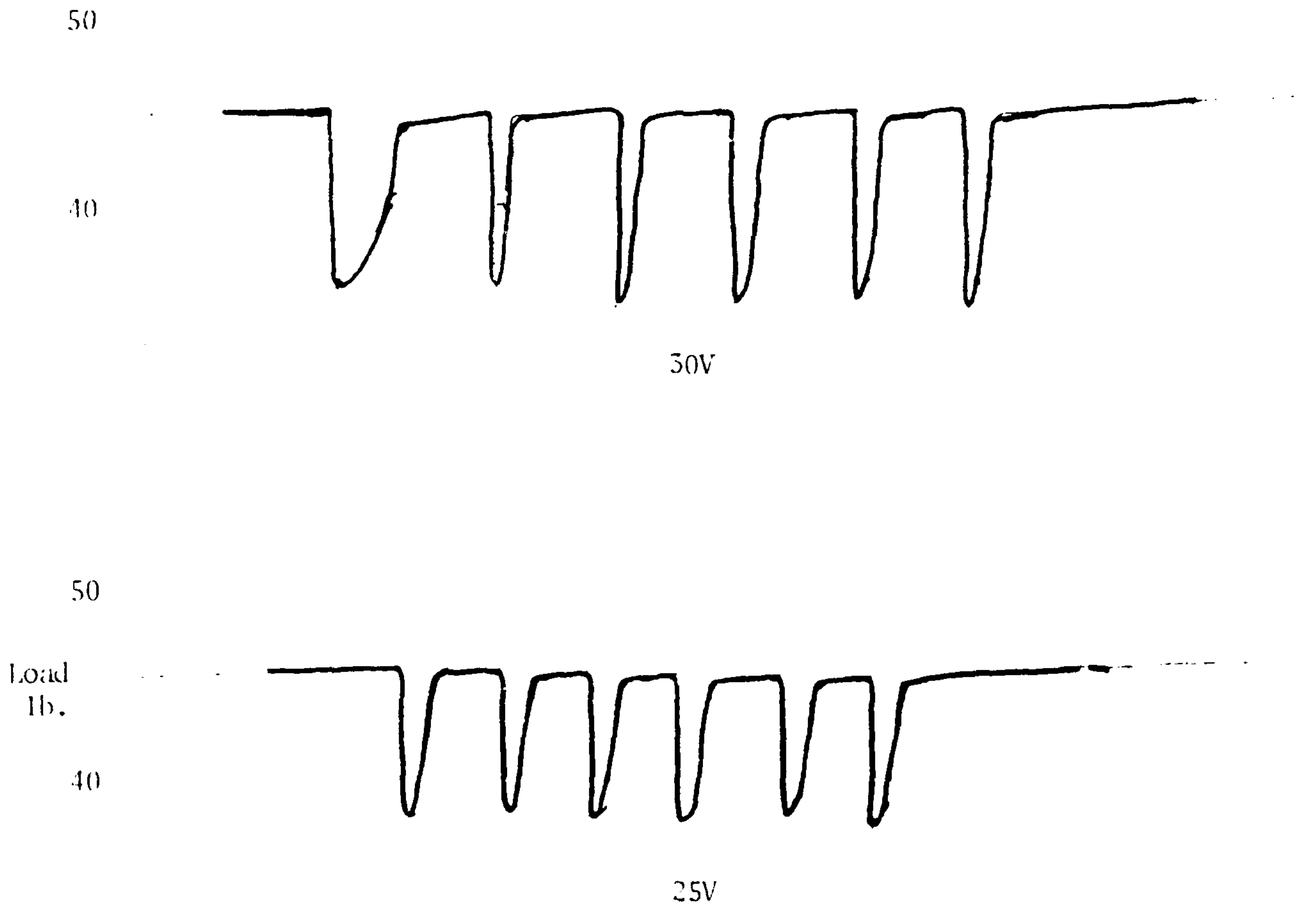


Figure 3: Schematic Diagram of Load Drops in Polycrystalline Al as a Function of Strain Rate.



Extension: 1" on Chart Equals .004" Extension

Figure 4: Load Drops in Al Single Crystals

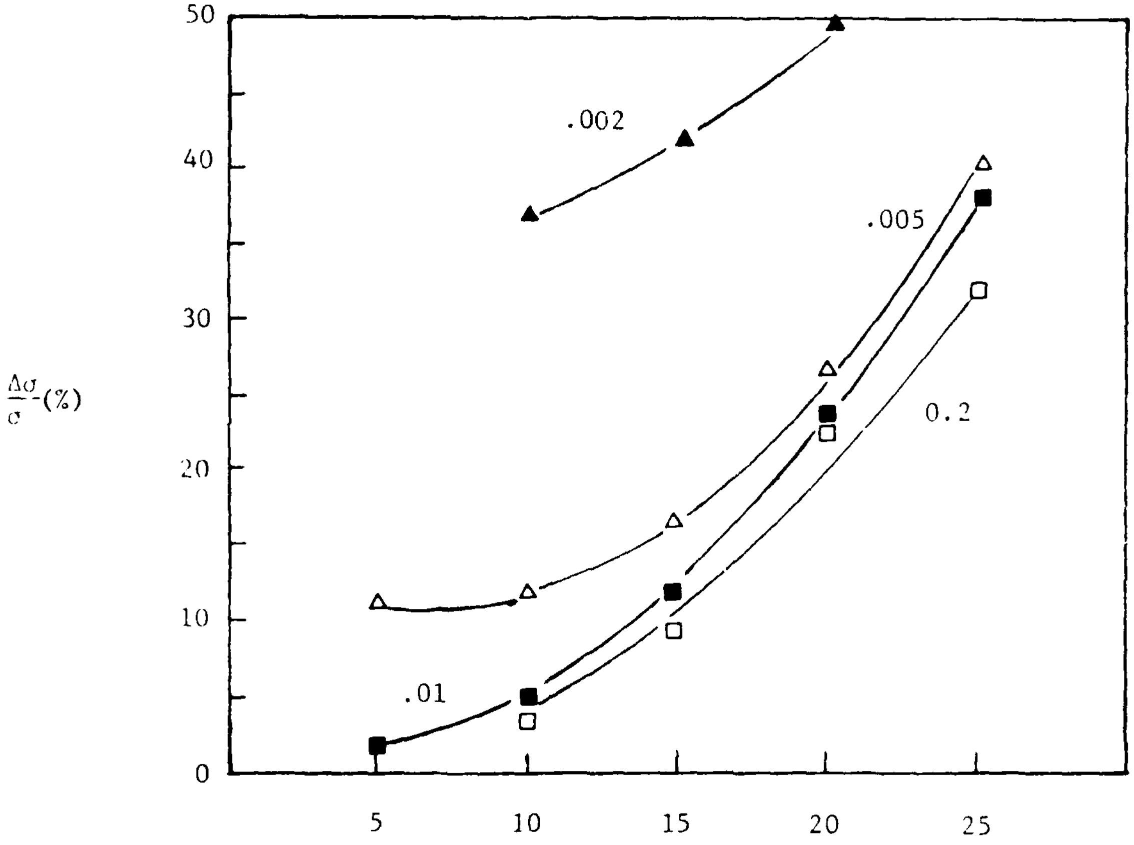


Figure 5: Effect of Voltage on % Load Drop in Al Single Crystals. Numbers on Curves are Cross Head Speeds in inch/min.

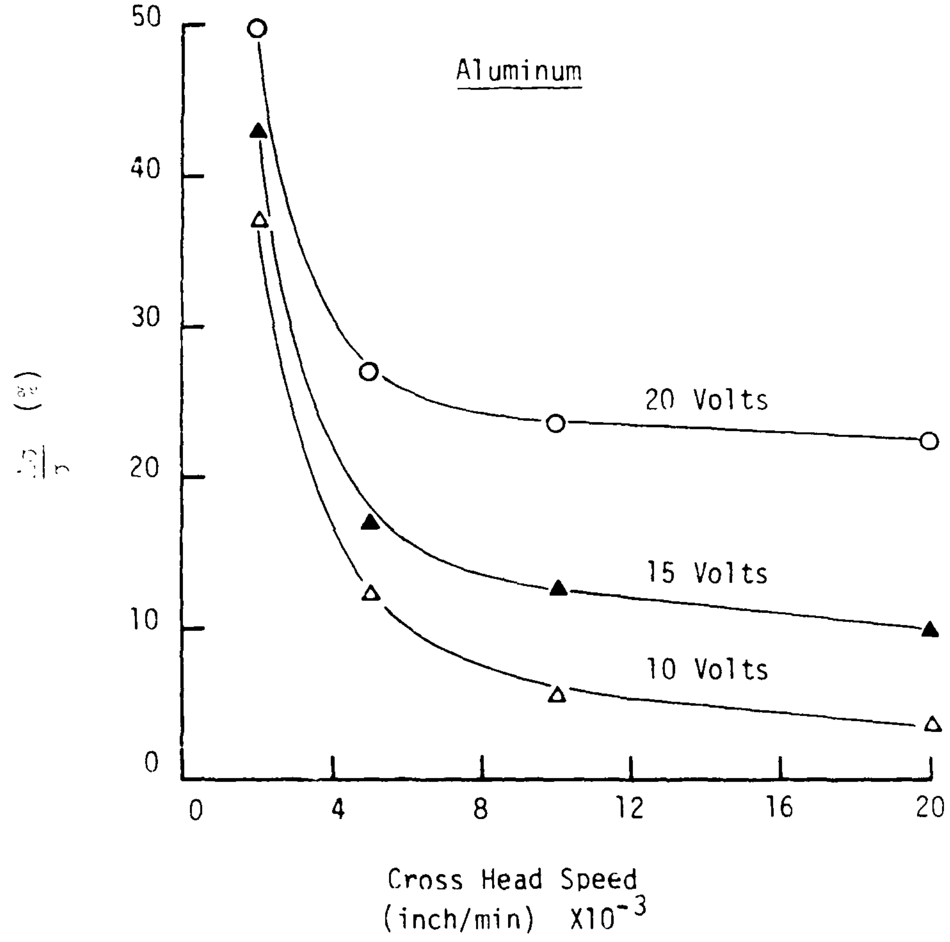


Figure 6: Effect of Strain Rate on % Load Drop in Al Single Crystal at Different Voltages